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Novel Substrates for Photodetectors

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This research has investigated epitaxial InSb, CdTe, MgCdTe, and CdTe/MgCdTe double heterostructures grown on InSb(100) substrates using molecular beam epitaxy. State-of-the-art materials materials quality has been successfully achieved in all of these materials, which have demonstrated record narrow X-ray diffraction line-widths, ultra-low defect density, and record long minority carrier lifetime of over 340 ns. These findings provide strong evidence that CdTe grown on InSb is highly suitable for use as a virtual substrate for multiple applications, including infrared detectors and the investigation of CdTe solar cells.

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Novel Virtual Substrates for Future Generation IR Photodetectors

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Abstract: This research has investigated epitaxial InSb, CdTe, MgCdTe, and CdTe/MgCdTe double heterostructures grown on InSb (100) substrates using molecular beam epitaxy. State-of-the-art materials quality has been successfully achieved in all of these materials, which have demonstrated record narrow X-ray diffraction line-widths, ultra-low defect density, and record long minority carrier lifetime of over 340 ns. All of these findings provide strong evidence that CdTe grown on InSb is highly suitable for use as a virtual substrate for multiple applications, including infrared detectors and the investigation of CdTe solar cells.

1. Objectives

The next generation of IR sensors is likely to be based on large-format (megapixel) arrays of photodetectors with multi-spectral band capabilities. HgCdTe alloys and type-II superlattices based on GaSb substrates have been shown to be ideal for future mid-wave infrared (MWIR) and long-wave infrared (LWIR) photodetector applications. These materials have to be grown on suitable substrates that have large areas enabling low manufacturing cost of the arrays, as well as having similar bonding properties, lattice constants, and thermal expansion coefficients. This research program was initially funded for three years but support was later reduced to a level sufficient only for a single year of research due to sequestration of federal funds. Thus, the scope of the proposed research had to be substantially curtailed, and effort was concentrated mainly on the growth and optical characterization of CdTe/InSb and exactly-lattice-matched CdZnTe/InSb heterostructures.

2. Research Highlights:

The CdTe/MgCdTe double heterostructures (DHs) were grown on InSb (001) substrates using molecular beam epitaxy [1] These materials revealed strong photoluminescence with over double the intensity of a GaAs/AlGaAs DH with an identical layer structure design grown on GaAs. Time-resolved photoluminescence of the CdTe/MgCdTe DH gave a Shockley-Read-Hall recombination lifetime of 179 ns, which was more than one order of magnitude longer than that of typical polycrystalline CdTe films. These findings indicated that the monocrystalline CdTe/MgCdTe DHs effectively reduced surface recombination, had limited non-radiative interface recombination, and were likely to be promising for solar cells that could reach power conversion efficiencies similar to that of GaAs.

The optical properties of the CdTe/MgCdTe double heterostructures were subsequently investigated in more detail [2]. Low-temperature photoluminescence showed strong band-to-band emission and very weak defect related peaks, indicating low defect densities. The measured Shockley–Read–Hall lifetimes ranged from 57 to 86ns at room temperature for samples grown under different conditions (see Figure 1.). The material radiative recombination coefficient B in the recombination rate defined as $R = A\Delta n + (1 - \gamma)\,\beta\Delta n^2 + C\Delta n^3$ was evaluated to be $4.3 \pm 0.5 \times 10^{-9}$ $cm^3.s^{-1}$ with a photon recycling factor c of 0.85 calculated based on the geometric structure of the samples.

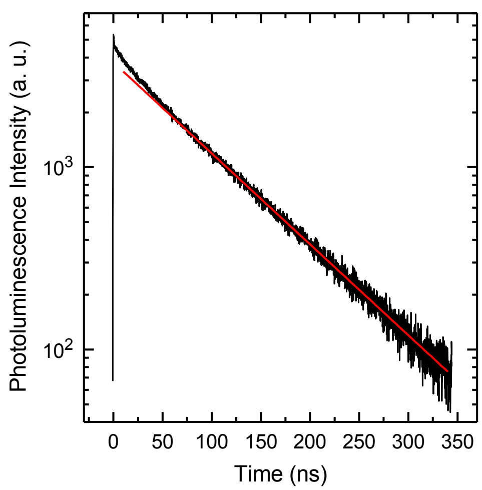

Fig. 1. Room temperature photoluminescence decay of a 1-μm-thick CdTe/MgCdTe DH showing a lifetime of 86ns.

Transmission electron microscopy imaging techniques were then used to investigate CdTe/$Mg_xCd_{1-x}Te$ (nominally x ~ 24%) double heterostructures grown by molecular beam epitaxy on (001) InSb substrates at temperatures in the range of 235 °C to 295 °C [3]. Defect analysis of bright-field electron micrographs indicated that the structure grown at 265 ºC had the best structural quality of the series, as shown by the example in Fig. 2,, while structures grown at 30 °C lower or higher temperature had defective morphology. Geometric phase analysis of the CdTe/InSb interface revealed strong tensile interfacial strain for the sample grown at high temperatures, suggesting the possible formation of an interfacial compound. However, there was no direct evidence visible in high-resolution electron micrographs of the interface region.

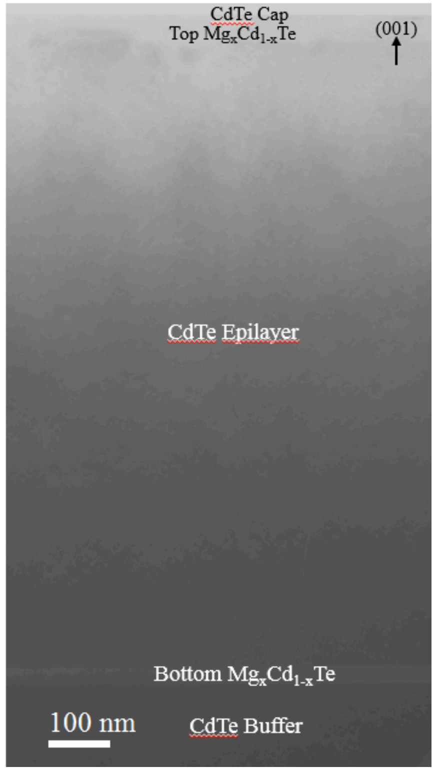

Fig. 2. Bright-field TEM image showing the high structural quality of a CdTe/MgCdTe DH grown at 265°C.

Confocal photoluminescence scans of these monocrystalline CdTe/MgCdTe double heterostructures epitaxially grown on lattice-matched InSb substrates revealed very low twin defect density, below 1×10^5 cm^{-2} [4] - see Fig. 3.

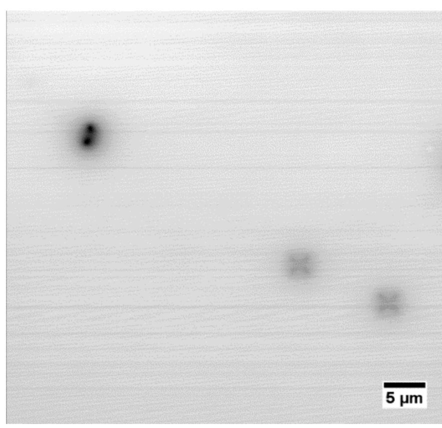

Fig. 3. Confocal photoluminescence mapping of the 1 μm CdTe/MgCdTe DH sample grown at optimal condition.

Room-temperature Shockley-Read-Hall (SRH) lifetimes of these samples were determined to be in the range of 35 ns to 86 ns using time-resolved photoluminescence (TRPL) measurements.

Temperature-dependent TRPL measurements showed that the carrier lifetime reached a peak of 910 ns at 200 K. Excitation-dependent PL measurements revealed the radiative recombination coefficient of CdTe to be 4.3×10^{-9} $cm^3 \cdot s^{-1}$. Figure 4 shows the temperature dependent PL intensity and lifetime, which indicates that the sample is dominated by radiative recombination at temperatures below 150 K.

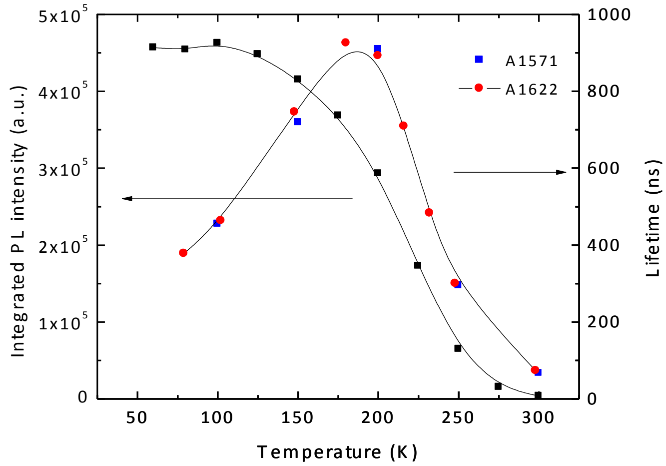

Fig. 4. Temperature dependent integrated PL intensity and carrier lifetime of CdTe/MgCdTe DH showing that the sample is radiative recombination dominated at temperatures below 150 K.

The bulk Shockley-Read-Hall carrier lifetime of CdTe and interface recombination velocity at the CdTe/$Mg_{0.24}Cd_{0.76}Te$ heterointerface were estimated to be around 0.5 μs and $(4.7 \pm 0.4) \times 10^2$ cm/s, respectively, using time-resolved photoluminescence (PL) measurements [5]. Four CdTe/MgCdTe double heterostructures (DHs) with varying CdTe layer thicknesses were grown on nearly lattice-matched InSb (001) substrates using molecular beam epitaxy. The longest lifetime of 179 ns was observed in the DH with a 2-μm-thick CdTe layer. It was also shown that the photon recycling effect had a strong influence on the bulk radiative lifetime, and the reabsorption process affected the measured PL spectrum shape and intensity.

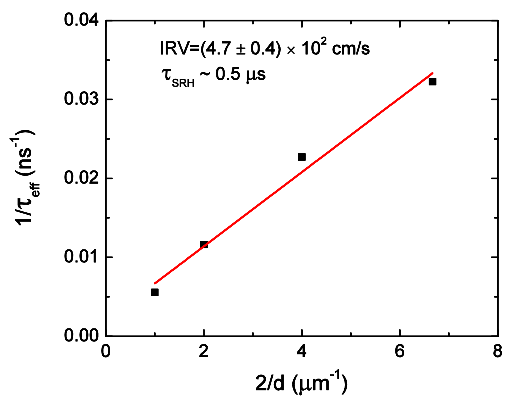

Fig. 5 Effective carrier lifetime τ_{eff} as a function of sample thickness d. The interface recombination velocity and the bulk Shockley-Read-Hall carrier lifetime are extracted to be $(4.7 \pm 0.4) \times 10^2$ cm/s and 0.5 μs respectively.

Finally, a CdZnTe alloy lattice-matched to InSb with a Zn composition of 0.54 % has been demonstrated with a long carrier lifetime of 340 ns observed in a 3-μm-thick CdZnTe/MgCdTe double-heterostructure (DH) grown on an InSb substrate. This lifetime is about three times that of a CdTe/MgCdTe DH with identical layer thickness [6]. This substantial improvement was attributed to the reduction in misfit dislocation density in the CdZnTe alloy as a result of complete lattice-matching to the substrate. On the contrary, the 3-μ-thick CdTe had a strain relaxation of ~30 % leading to a wider X-ray diffraction peak, a weaker integrated photoluminescence intensity, and shorter minority carrier lifetime. The findings indicated that CdZnTe lattice-matched to InSb is promising for high-efficiency solar cells with large open-circuit voltages, as well as virtual substrate applications for high-performance large-area HgCdTe focal plane arrays.

3. List of Publications

[1] M.J. DiNezza, X.-H. Zhao, S. Liu, A.P. Kirk, and Y.-H. Zhang, "Growth, steady-state, and time-resolved photoluminescence study of CdTe/MgCdTe double heterostructures on InSb substrates using molecular beam epitaxy", Appl. Phys. Lett. **103**, 193901 (2013).

[2] X.-H. Zhao, M.J. DiNezza, S. Liu, S. Lin, Y. Zhao, and Y.-H. Zhang, "Time-resolved and excitation-dependent photoluminescence study of CdTe/MgCdTe double heterostructures grown by molecular beam epitaxy", J. Vac. Sci. Technol. B **32**, 040601 (2014).

[3] J. Lu, M.J. DiNezza, X.-H. Zhao, S. Liu, Y.-H. Zhang, and D.J. Smith, "TEM study of defects and interfaces of epitaxial CdTe and InSb layers grown on InSb (001) substrates, J. Cryst. Growth, submitted for publication.

[4] X.-H. Zhao, M.J. DiNezza, S. Liu, P.A.R.D. Jayathilaka, O.C. Noriega, T.H. Myers,, and Y.-H. Zhang, "Temperature-dependent time-resolved photoluminescence study of monocrystalline CdTe/MgCdTe double heterostructures with low defect density", Proc. 2014 PVSC Conf, submitted for publication.

[5] X.-H. Zhao, M.J. DiNezza, S. Liu, C.M. Campbell, Y. Zhao, and Y.-H. Zhang, "Determination of CdTe bulk carrier lifetime and interface recombination velocity of CdTe/MgCdTe double heterostructures grown by molecular beam epitaxy", Appl. Phys. Lett., accepted for publication.

[6] S. Liu, X.-H. Zhao, C.M. Campbell, M.J. DiNezza, Y. Zhao, and Y.-H. Zhang, "Minority carrier lifetime of lattice-matched CdZnTe alloy grown on InSb substrates using molecular beam epitaxy", J. Vac. Sci. Technol. B, accepted for publication.

ii) Conference presentations

[1] M. J. DiNezza, X.-H. Zhao, S. Liu and Y.-H. Zhang, "MBE growth and photoluminescence study of CdTe/CdMgTe double heterostructures on InSb substrates," 30th North American Molecular Beam Epitaxy Conference, Banff, Canada, Oct. 5-11, 2013.

[2] Xin-Hao Zhao, Michael DiNezza, Jing Lu, Shi Liu, David Smith, Yong-Hang Zhang, "Structural and optical properties of CdTe/MgCdTe single and double heterostructures grown on InSb using MBE", U.S. Workshop on the Physics & Chemistry of II-VI materials, Chicago, IL, Oct. 2013.

[3] Xin-Hao Zhao, Michael J. DiNezza, Shi Liu, Pathiraja A. R. D. Jayathilaka, Odille C. Noriega, Thomas H. Myers, and Yong-Hang Zhang, "Temperature-dependent time-resolved photoluminescence study of monocrystalline CdTe/MgCdTe double heterostructures with low defect density", 40th IEEE Photovoltaics Specialist Conference, Denver, CO, Jun. 8-13, 2014.

[4] J. Lu, M.J. DiNezza, X.-H. Zhaoi, S. Liu, Y.-H. Zhang, and D.J. Smith, "TEM study of defects and interfaces of epitaxial CdTe and InSb layers grown on InSb(001) substrates, presented at International MBE Conference", International MBE Conference, Flagstaff, AZ, September 8-12, 2014.

[5] X.-H Zhao, M. J. DiNezza, S. Liu, E. G. LeBlanc, P. Jayathilaka, O. C. Noriega, T. H. Myers, and Y.-H. Zhang, "CdTe/MgCdTe Double Heterostructures Grown on InSb for Photovoltaic Devices", 18th International MBE Conference, Flagstaff, AZ, September 8-12, 2014.

[6] X.-H Zhao, M. J. DiNezza, S. Liu, Y.-S. Kuo, C. Campbell, Y. Zhao, and Y.-H Zhang, "Low interface recombination velocity in MBE grown CdTe/MgCdTe double heterostructures", U.S. Workshop on the Physics & Chemistry of II-VI Materials, Baltimore, MD, Oct. 21-23, 2014.